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A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River

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Abstract: Water discharge and sediment load have changed continuously during the last half century in the Yellow River basin, China. In the present paper, data from 7 river gauging stations and 175 meteorological stations are analyzed in order to estimate quantitatively the contributions of human activities and climate change to hydrological response. Coefficients of water discharge (C_w) and sediment load (C_s) are calculated for the baseline period of 1950s~1960s according to the correlations between the respective hydrological series and regional precipitation. Consequently, the natural water discharge and natural sediment load time series are reconstructed from 1960s~2008. Inter-annual impacts are then separated from the impacts of human activities and climate change on the hydrological response of different regions of the Yellow River basin. It is found that human activities have the greatest influence on changes to the hydrological series of water discharge and sediment load, no matter whether the effect is negative or positive. Moreover, the impact of human activities is considerably greater on water discharge than sediment load. During 1970~2008, climate change and human activities respectively contribute 17% and 83% to the reduction in water discharge, and 14% and 86% to the reduction in sediment yield in the Upper reaches of Yellow River basin; The corresponding relative contributions in the Middle reaches are 71% and 29% to reductions in water discharge, and 48% and 52% to reductions in sediment load. Moreover, it is observed that the impacts of human activities on the whole basin are enhanced with time. In the 2000s, the impact of human activities exceeds that of climate change in the 2000s, with human activities directly responsible for 55% and 54% of the reductions in water discharge and sediment load in the whole basin.

Keywords: Yellow River; water discharge; sediment load; climate change; human activity;

1. Introduction

The Earth's physical environment has been varying under natural driving forces (Ren et al., 2002), and these variations have been further complicated by increasingly intensive human activities. Climate observations indicate that, during the 20th Century, global annual precipitation increased significantly at a rate of ~ 0.2 mm/year^2 ($P < 0.001$) (Piao et al., 2007), and global surface temperature increased by ~ 0.8℃ (Hansen et al., 2006) with a significant upwards trend over the past 30 years of 0.2℃ per decade. Global climate change has in turn influenced global and regional hydrological cycles. Moreover, human activities (such as land use change, soil and water conservation practices, reservoir construction and operation, irrigation, water abstraction, etc.) have also disturbed river systems.

Consequently, the response of rivers to changing climate and human activities is an important topic in hydrology and has elicited many qualitative studies (see e.g. Arnell and Reynard, 1996; Ren et al., 2002; Walling and Fang, 2003; Wang et al., 2006a; Cai et al., 2008; Liquete et al., 2009; Xu and Ma, 2009). However, quantitative assessments of climate and human impacts on long-term hydrologic response are very important for drainage basin management. Labat et al. (2004) estimated that an additional 4% of global runoff could arise from an increase of 1℃ in global temperature. Piao et al. (2007) suggested that changes in climate and land use can have a larger direct impact than increased CO_2 levels on global river runoff trends, and note that land-use change has increased global runoff by an average of 0.08 mm/yr, accounting for about half the reconstructed global runoff trend over the last century. In the late 1980s, Meybeck (1988) estimated the cumulative sediment load intercepted by reservoirs was 1.5 Gt/yr, equivalent to 7.5 ~ 10% of the total natural river mouth flux. More recently, Vörösmarty et al. (2003) produced a much larger estimate of 28% based on a much more comprehensive survey of basins worldwide. Syvitski et al. (2005) estimated that anthropogenic influences have simultaneously increased sediment transport by global rivers through soil erosion (2.3 ± 0.6 billion t/yr) while reducing the flux of sediment reaching the world's coast (1.4 ± 0.3 billion t/yr) due to retention by reservoirs.

As the second largest river in China, the Yellow River is culturally and archaeologically important as the birthplace of Chinese civilization. The Yellow River has relatively low water discharge yet huge sediment load. Under the influences of global climate change and intensive human activities, coupled with the harsh natural conditions and fragile ecosystem, great changes have recently taken place to the eco-environment of the Yellow River basin (see e.g. Wang and Cheng, 2000). For example, the water discharge and sediment load in the Yellow River have declined significantly over the past fifty years (e.g. Yang et al., 2004; Xu, 2005a; Liu and Zheng, 2004; Fu et al., 2004; Wu et al., 2008; Xu, 2005b; Wang et al., 2006b; Miao et al., 2010). In the Yellow River basin, due to its vital national (cultural, environmental, functional) importance and the delicate balance of its river system, quantitative assessments of climate change and human impacts on the hydrological response of the basin are invaluable to government agencies and policy makers. The methodologies involved in making such assessments include empirical analysis based on hydrometric and meteorological data, physical model tests, and field observations under different land use and land cover conditions. Liu and Zhang (2004) found that reduced precipitation in the 1990s was directly responsible for 75% and 43% of the reductions in river discharge in the upper and middle drainage basins. Zheng et al. (2009) reported that changes in land use were responsible for more than 70% of the decrease in streamflow of the headwater sub-catchments of the Yellow River basin that occurred in the 1990s. Chen et al. (2004) estimated that soil and water conservation practices implemented during the 1950s~1980s caused a 6.5% reduction in runoff in the Yanhe River, a sub-basin of the Yellow River; Li et al (2007) reported that the soil conservation measures in the period from 1972 to 1997 accounted for 87% of the total reduction in mean annual streamflow in the Wuding River, another sub-basin of the Yellow River; Mou (1996) analyzed the changes in the sediment load contributed by the middle Yellow River basin as a result of soil and water conservation during the 1980s; Wang et al. (2007) estimated that the average decrease in sediment yield due to soil conservation practices from 1969 to 1999 was 0.24Gt/yr in the Yellow River basin. Rustomji et al. (2008) estimated that the catchment management practices aimed at reducing soil erosion contributed 64% to 89% of the reduction in annual sediment yield in the Hekou~Lonmen area during the 1950s~1990s; Xu (2004) suggested that precipitation and erosion control measures were almost equally responsible for changes to the sediment load in the period from 1970 to 1996 in Wuding River.

Several publications discuss the quantitative assessment of human and natural contributions to changes in water discharge and sediment load in Yellow River (Mou, 1996; Liu and Zhang, 2004; Xu, 2004; Chen et al., 2004; Li et al., 2007; Wang et al., 2007; Rustomji et al., 2008; Zheng et al., 2009; Fu et al., 2009). However, most of these previous studies focus solely on sub-catchments of the Yellow River basin, not the whole watershed system. In addition, the studies have mostly concentrated on periods between the start of the 1960s to the end of the 1990s. However, a huge project "Grain for Green" (GFG), costing more than 30 billion US dollars, was launched by the Chinese government at the end of 1999, and implemented countrywide until 2002 (Miao et al., 2010). The objective of this program was to increase vegetation coverage on steep hillsides by planting trees or sowing grass on former cropland. As a consequence, research studies undertaken before 2000 only give a partial picture of the impact of human activities on the Yellow River basin. The goal of the present work is to make a systematic, quantitative analysis of the water discharge and sediment load responses of the entire Yellow River basin to changes in human activities and climate. It is hoped that the present study will contribute to a better understanding of the mechanisms controlling the interaction between human beings and nature, while also providing a stronger base for decision-making concerning environmental management of the Yellow River basin.

2. The Yellow River basin

The Yellow River basin has a catchment area of about 753,000 km^2, located between 96°~119° E longitude and 32°~42° N latitude. The length of the main river channel is about 5,464 km (Figure 1). The source of the Yellow River is in the Tibetan plateau. It then flows through the semi-arid region of north China, the Loess Plateau, and the eastern plain, before discharging into the Pacific Ocean (Xu and Ma, 2009). About 110 million people were recorded as inhabiting the drainage area in 2000. The catchment contains 12.6 million ha of farmland, with the Yellow River providing water for the 40% of farmland that is under irrigation (Xia et al., 2002). Miao et al. (2010) list the characteristics of the Upper (above Hekou), Middle (between Hekou and Huayuankou); and Lower (below Huayuankou) reaches of Yellow River.

Figure 1

3. Data and methods

3.1 Data

The present study utilizes hydrologic data from the seven gauging stations listed in Table 1. The observed series cover the period from the 1950s to 2008. Figure 1 and Table 1 provide information on the station locations, associated drainage area, annual mean water discharge, and annual mean sediment load over the entire period of observations. The Yellow River Water Conservancy Commission (YRCC) supplied the data acquired before 2000. The data since 2000 were extracted from the China Water Resources Bulletin (Ministry of Water Resources, MWR).

Annual regional precipitation series from the 1950s to 2008 were interpolated by the Inverse Distance Weighted (IDW) method from data from 175 meteorological stations, provided by the National Meteorological Information Center, China Meteorological Administration. Figure 1 shows the locations of these stations in and around the Yellow River basin.

Table 1

3.2 Methodology

In the Yellow River basin, the area over which erosion control measures have been implemented has rapidly expanded since the 1970s (Wang et al, 2006a; Cong et al., 2009; Miao et al., 2010). In order to separate and quantify the influences of climate change and local human activities on streamflow and sediment load variations, the 1950s~1960s are taken as the baseline (benchmark) period. Moreover, the dates at which large reservoirs became operational are also taken into account when specifying temporal divisions separating different periods (Figure 1). Herein, human impacts during the baseline period are assumed to be negligible. The present research is therefore concerned with the relative acceleration and intensification of human activities after the baseline period. For the successive decades thereafter, i.e. 1970s, 1980s, 1990s and 2000s, variations of water discharge and sediment load in response to climate change are quantified by reconstructing the natural streamflow and natural sediment load from the runoff coefficient (C_r) and sediment load coefficient (C_s).

Baseline period values of water discharge coefficient (C_w) and sediment load coefficient (C_s) are calculated according to regression fits between annual regional precipitation and annual water discharge, and annual regional precipitation and annual sediment load. The coefficients respectively describe the yields of water discharge and sediment load per unit precipitation. The basin natural streamflow and natural sediment load are then simulated for subsequent decades ignoring the effect of local human activities on drainage (i.e. land use change, irrigation, abstraction, and treated effluent input). Hence, changes to the reconstructed water discharge (R_w) and sediment load (R_c) are hypothetically due solely to the hydrological response to climate change (mainly precipitation in the Yellow River basin). Likewise, the change in streamflow due to human activities is denoted as H_w, and the change in sediment load due to human activities is denoted as H_s. Thus, hydrological response to human activities is given by (i) the difference between the reconstructed natural water discharge (R_w) and the actual (measured) discharge, and (ii) the difference between the reconstructed sediment load (R_c) and the observed sediment load. Figure 2 depicts the baseline data, reconstructed data, and observed data on sediment load at Hekou Station. In this case, it is easy to see the quantitative hydrological response to climate change and human activities; Interval ① in Figure 2 indicates the impact of climate change;

Interval ② shows the impact of human activities.

Figure 2

4. Results

4.1 Water discharge coefficient (C_w) and sediment load coefficient (C_s)

Correlations between the annual regional precipitation and water discharge, and annual regional precipitation and sediment load have been analyzed for different drainage areas, taking account of dates when reservoir operation started. Figure 3 presents the results of the regression analyses for each of the hydrological stations. It can be seen that all the correlations between annual precipitation and annual water discharge are significant over the 99% confidence level, which demonstrates the direct influence of precipitation on water discharge during the baseline periods. Similar significant relationships between the annual regional precipitation and sediment load appear, except at Sanmenxia.

Figure 3

Table 2 lists the water discharge and sediment load coefficients obtained for the different drainage areas from regression analysis. The hydrological series related to Table 2 and Figure 3 are direct observations sampled at the hydrological stations. Hence, the data (i.e. water discharge, sediment load, C_w, C_s) at a given station inevitably contain some information related to the upstream station. For example, at Lanzhou station, C_w = 0.442, which includes the influence of the reach upstream of Tangnaihai where C_w = 0.475 in addition to that of the Tangnaihai~Lanzhou area. The value of C_w for the Tangnaihai~Lanzhou area is readily calculated according to the relevant proportion of water discharge. Downstream of Lanzhou, C_w decreases significantly in the Hekou and Longmen drainage areas, the latter having a minimum value of 0.186. C_w rises slightly in the drainage area downstream of Sanmenxia, reaching 0.312 at Lijin. However, the sediment load coefficient C_s has entirely different spatial characteristics; C_s increases significantly from 0.621 to 4.02 in the Tangnaihai~Hekou drainage area, and attains a peak value of 15.2 in the Hekou~Lijin drainage area.

Table 2

4.2 Decadal variations in precipitation, water discharge and sediment load

Table 3 lists the decadal mean annual precipitation, mean annual discharge, and mean annual sediment loads. The table also presents the percentage difference with respect to the baseline value. It can be seen that both the reconstructed water discharge and reconstructed sediment load are close to the observed data in the baseline periods, which gives confidence in the simulated values obtained for the 1970s~2000s. During 1970s~1980s, the decadal precipitation increased in the drainage area above Lanzhou, and this had a positive effect on the generation of runoff, which directly increased the reconstructed water discharge and reconstructed sediment load.

Except for Tangnaihai, the water discharge and sediment load series during 1970s~2000s have lower values than during the baseline periods, with the levels of reduction growing larger with time. In the same period, the declining trends in water discharge and sediment load series both intensified in the downstream direction. Of the seven hydrological stations, the most significant decreases in the water discharge series occur in the 1980s at Huayuankou, where the rates of reduction are 41.3×10^9 m^3/yr and 41.2×10^9 m^3/yr for the observed and reconstructed series respectively. However the greatest percentage changes occur in the 1990s at Lijin with 68% and 36% reductions. The largest changes in observed and reconstructed sediment load series occur at different time periods (unlike the water discharge series). For the observed sediment load series, the greatest change occurs in the 1970s at Sanmenxia where there is a reduction of 1398×10^6 t/yr, whereas the greatest percentage change occurs in the 2000s at Huayuankou with 92 % reduction. For the reconstructed sediment load series, the greatest change occurs in the 1980s at Sanmenxia with a reduction of 1468.4×10^6 t/yr, whereas the greatest percentage change occurs in the 1990s at Lijin with 47% reduction.

Table 3

4.3 Quantitative hydrological response to climate change and human activities

Table 4 summarizes the contributions of climate change and human activities to the variations in water discharge and sediment load. It should be noted that these contributions can have either negative or positive effects on the hydrological series. For example, wetter (or drier) weather during a period of climate change potentially increases (or reduces) the streamflow, and hence influences the sediment load. And for human activities, irrational tillage, such as downslope cultivation and steep-sloped reclamation, has a negative influence on decreasing sediment load, whereas the construction of check dams and reservoirs has a positive influence on decreasing sediment load. The diversion of water led to a positive influence on decreasing streamflow. The data listed in Table 4 are arithmetic average values, whose sign reflects the direction of dominant impacts. It should be noted that certain of the largest percentage changes are due to the small total change in the denominator. In general, it is evident that human activities contribute more much to changes in the hydrological series, no matter whether the effect is negative or positive. And the percentage impacts of human activities are much larger on the water discharge than the sediment load.

The least impact by human activities on sediment load is experienced by the drainage area above Tangnaihai. Both climate change and human activities in the Hekou~Longmen area result in decreasing water discharge and sediment load over all the periods considered. In addition, human activities in the Tangnaihai~Sanmenxia drainage area also reduce the values of the hydrological series, unlike the Sanmenxia~Huayuankou drainage area where the values increase. Human activities in the Hekou~Longmen area have caused the greatest reductions in water discharge and sediment load, compared with other regions, and these reductions intensify over time. In the drainage area above Lanzhou, climate change causes alternating, but somewhat inconsistent, negative and positive impacts on water discharge and sediment load (Table 4). The most significant human impacts occur in the 2000s and are the 5.10×10^9 m^3/yr change in water discharge in the Longmen~Sanmenxia area, and the 549.1×10^6 t/yr change in sediment load in the Hekou~Longmen area.

Only in the Upper reaches of the Yellow River basin do climate change and human activities have a negative effect on water discharge and sediment load. The most significant impact on water discharge change is a reduction of about 8.58×10^9 m^3/yr, which appears after 2000 in the Upper reaches, and is due to human activities. Meanwhile, the most notable impact on sediment load is the decrease of about 855.3× 10^6 t/yr that occurs in the Middle reaches, which is also caused by human activities in the 2000s.

During 1970~2008, climate change and human activities relatively contribute 17% and 83% to the reductions in water discharge respectively, and 14% and 86% to the reductions in sediment yield in the Upper reaches of Yellow River basin. The corresponding percentage contributions for the Middle reaches are 71% and 29% to changes in water discharge, and 48% and 52% to changes in sediment load. By regarding the Yellow River basin as a whole entity, it is obvious that the impacts of human activities on changes to the hydrological series have been increasing almost monotonically over the past forty years (Table 4). For water discharge and sediment load, the impact of human activities far exceeds that of climate change during the 2000s. Human activities in the whole basin in the 2000s are directly responsible for the 55% and 54% reductions in water discharge and sediment load.

Table 4

5. Discussion

The hydrology of the Yellow River basin is characterized by the fact that the major source areas of runoff do not coincide with the major source areas of sediment (Xu, 2003). For example, the drainage area upstream of Lanzhou supplies about 52% of the annual water discharge and only 9% of the total river sediment load, whereas the middle reaches contribute about 43% of the water flow and more than 90% of the annual sediment load (especially in the Hekou~Longmen area) because of severe erosion of the Loess Plateau.

In the upper reaches of Yellow River basin, especially in the drainage area upstream of Tangnaihai, the population is small due to the comparatively inhospitable natural conditions (e.g. high altitude, low temperature, etc.), and hence human activities at small scale are relatively weak. However, due to the abundance of water resources in this area, human activities at large scale inevitably have a great influence on the water discharge. Compared with the other regions, the impacts of human activities on water discharge are most significant in the upper reaches (Table 4). Human activities at large scale include hyper-irrigation and large hydroelectric projects. According to statistical data from the Ministry of Water Resources, hyper-irrigation of the upper reaches of Yellow River basin occupies an area of about 12,340 km^2, of which more than 94% is located in the Lanzhou~Hekou area (Table 5). Hyper-irrigation directly reduces the regional water discharge because of water consumption by new irrigation fields. Moreover, large hydroelectric projects (including reservoirs at Longyangxia, Liujiaxia, Qingtongxia and Sanshenggong, etc.) are located in this area (Figure 1), and the associated siltation capacity of the tributary reservoirs has kept increasing over the year (Table 6). These reservoirs not only redistribute the seasonal water discharge and sediment load within any given year, but also adjust their inter-annual distribution.

Table 5

Table 6

In the Middle reaches of the Yellow River basin, severe soil loss, which can exceed 20,000 t/km/yr in certain areas (Fu and Chen, 2000), provides > 90% of the total river sediment load. Soil conservation practices (such as afforestation, grass-planting, creation of level terraces, and building check dams, etc.) have been implemented since 1949, once the severity of soil loss was recognized (Liu, 2005). These soil conservation practices change local micro-topography, intercept precipitation, improve the infiltration rate of water flow, slow down or retain the runoff and sediment load, and consequently delay or even reduce runoff and sediment generation. From Table 7 and Figure 4, it can be seen that the soil conservation area has expanded with time. Table 8 lists the effects of different soil conservation practices, expressed as ratios based on the volume of runoff to area and the sediment load to area. It is hence found that the measures against soil erosion became increasingly effective, particularly after the late 1970s - in keeping with the results in Table 4. Even so, the irrigation area in Hekou~Sanmenxia is larger than that in Sanmenxia~Huayuankou (Table 5), and consequently causes a greater reduction of water discharge in Sanmenxia~Huayuankou (Table 4).

Table 7

Figure 4

Table 8

In the Lower reaches, hydrological change results from the combination of contributory effects from the local region, and the Upper and Middle reaches of the Yellow River basin. Due to the flat topography of the Lower Yellow River sub-basin, much uncultivated land was converted into irrigation areas in order to meet the food requirements of the growing population. Especially in the 1970s and 1980s, the irrigation areas were extended outside the basin along the lower reaches from Huayuankou (Yang et al., 2004), and such areas presently occupy more than 70% of the total irrigation area in the Yellow River basin (Table 5). Irrigation-based agriculture with high grain yield partially alleviates the potential food shortage, but the local water resources are insufficient to meet the water requirements for such irrigation schemes. Although water diversion from the main river channel may seemingly solve this problem, this is at the cost of subsequent reduction in downstream flow (Table 4). What makes matters worse is the high cost of water consumption due to the low efficiency of water utilization. Li (2003) estimates that water diverted from the Yellow River for irrigation-based agriculture accounts for only 30% to 45% of the total irrigation water; the remainder is due to extensive floodwater irrigation. The irrigation water-use ratio (defined as annual gross water transfer to irrigation divided by annual runoff) has increased from 21% to 68% during the last 50 years (Yang et al., 2004). In addition, the decreasing precipitation in this area contributes to reduced streamflow (Table 3). Consequently, water shortages have become increasingly severe, with the main river along the lower reaches drying up during each irrigation season since 1972. The duration of the drought periods increased rapidly in the 1990s (Yang et al., 2004), with the most serious drought occurring in 1997 when 226 days of no-flow events were recorded at Lijin. The sediment load impacted by human activities in this area is of particular interest in comparison with the other regions. In general, human activities increased the sediment load during 1970~2008. The Lower reaches of Yellow River can be divided into three sub regions: Huayuankou~Gaocun, Gaocun~Aishan and Aishan~Lijin (Xu, 2003). In these three sub regions, the channel width to depth ratio is 662, 163, 126, and the channel sinuosity is 1.15, 1.33, 1.22, respectively. In the downstream direction, the channel becomes deeper, narrower and more stable. The sediment transport capacity is weakened because of the decreasing streamflow. Given the plentiful supply of sediment from the rapidly eroding Middle reaches of Yellow River basin, the sediment became deposited as the streamflow slowed, leading to a rising riverbed. Zhang et al. (1990) found that 90~95% of suspended sediment was deposited in the Lower Yellow River and less than 5~10% escaped Laizhou Bay and entered the Central Bohai and North Huanghai coastal waters. Heavy sedimentation in the lower reaches of the channel caused the riverbed to be aggraded by several centimeters per year. In places the riverbed has risen more than 10 m above neighboring land, causing the so-called "hanging river" phenomenon (Wang et al., 2005). What is more, construction of the Sanmenxia reservoir radically altered the hyper-concentrated characteristics of the downstream flow as well as the channel conditions. The bed elevation at Tongguan (located in the backwater region, a distance of 113.5 km upstream of Sanmenxia Reservoir) has been steadily increasing since Sanmenxia Reservoir started operation. Figure 5 shows the variation with time of the bed elevation at Tongguan from 1950 to 2008 (YRCC, 2009). It can be seen that the bankfull discharge of the Lower Yellow River has undergone significant abrupt changes at certain times, e.g. from 1960 to 1965, due to the construction of Sanmenxia Reservoir and the changing modes of reservoir operation.

Figure 5

It is obvious that the impacts of human activities on the hydrological cycle have grown considerably in recent times, and exceeded the impact of climate change after 2000 in the Yellow River basin (Table 4). So, how to utilize water resource effectively, manage and control river flow reasonably, are challenges that are very relevant to local human survival and development.

As is well known, groundwater impacts greatly on the surface water discharge, and so influences the sediment yield. While interacting with the surface water discharge, the groundwater reservoir supplies or stores water in dry or wet seasons. It is found that the average annual groundwater baseflow does not vary significantly during 1960~1990 in the Yellow River (Figure 6), with < 10% change at any station. After 1990, the percentage changes increase significantly, the largest change occurring at Huayuankou with a 37% reduction. The considerable decrease in groundwater can be attributed to human activities related to water diversion (Liu and Zhang, 2004; Lin and Wang, 2006). Abstraction of water from aquifers led to a consequent decrease in groundwater. Furthermore, this groundwater had to be replenished by water from surface runoff, thus reducing the surface water discharge. In the present study, due to the groundwater dynamics, the indirect influences from human activity on water discharge are already taken into account.

Figure 6

6. Conclusions

Previous studies have identified global and regional climate changes (mainly precipitation) and local human activities as the two main causative factors that impact on the hydrological cycle. In this preliminary study, we have estimated the relative contributions of human activities and climate change to the hydrological response of the Yellow River Basin. It is found that human activities and climate change have impacts that are spatially dependent. Upper reaches supply the major portion of the streamflow. Middle reaches provide most of the total river sediment. Human activities have made a greater contribution than climate change to altering the hydrological series of water discharge and sediment load, regardless whether the effect is negative or positive.

The total change to the streamflow discharge caused by human activities is most significant in the Upper reaches due to the relative abundance of water resource there. The Upper reaches are minor source areas for sediment, leading to relatively low absolute changes in sediment load there, although the percentage changes are still high. It is estimated that, during 1970~2008, climate change and human activities relatively contribute to 17% and 83% of the reduction in water discharge, and 14% and 86% of the reduction in sediment yield in the Upper reaches of Yellow River basin.

More than 90% of the total river sediment originates from the Middle reaches of Yellow River basin, in particular the rapidly eroding Loess Plateau. Large-scale soil conservation practices (such as afforestation, grass-planting, creation of level terraces, and the building of check dams, etc.) have successfully delayed or even reduced both runoff and sediment generation in the Middle Yellow River basin. During 1970~2008, the relative contributions of climate change and human activities were 71% and 29% reductions in water discharge, and 48% and 52% reductions in sediment load in the Middle reaches.

In the Lower reaches, the large irrigation area and low water utilization ratio have led to local over-consumption of water resources. Climate change and human activities during 1970~2008 are respectively responsible for 72% and 28% of the reduction in river discharge in the Lower drainage basin. Owing to the deposited sediment, the riverbed has risen significantly over the past half century. The sedimentation has re-shaped the river channel and altered the bankfull discharge. And, the operation of Sanmenxia reservoir has further complicated the river flow.

In general, the impacts of human activities on the whole Yellow River basin have become ever greater with time. Human activities in the whole basin in the 2000s are directly responsible for the 55% and 54% of the reductions in water discharge and sediment load.

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Table Captions

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Table 1. Detailed information of hydrological stations in the Yellow River basin

No.	Station name	Data period	Drainage area ($10^3 \times km^2$)	Average water discharge ($10^9 \times m^3/a$)	Average sediment Load ($10^6 \times t/a$)
1	Tangnaihai	1956~2008	122	19.8	12.7
2	Lanzhou	1950~2008	223	30.9	67.7
3	Hekou	1950~2008	368	21.6	106
4	Longmen	1950~2008	498	26.6	720
5	Sanmenxia	1950~2008	688	34.5	1069
6	Huayuankou	1950~2008	730	38.0	917
7	Lijin	1950~2008	752	31.3	756

Table 2. Regression equation and coefficients of water discharge and sediment in the baseline periods

Objects	Station	Baseline period	Regression equation [a]	C_w or C_s	Significance
Water discharge	Tangnaihai	1956~1969	y=0.475x-10.8	0.475	P<0.001
	Lanzhou	1950~1969	y=0.442x-13.7	0.442	P<0.001
	Hekou	1950~1965	y=0.246x-11.3	0.246	P<0.001
	Longmen	1950~1965	y=0.186x-7.09	0.186	P<0.001
	Sanmenxia	1950~1959	y=0.223x-29.1	0.223	P<0.001
	Huayuankou	1950~1959	y=0.293x-56.3	0.293	P<0.001
	Lijin	1950~1959	y=0.312x-74.3	0.312	P<0.005
Sediment load	Tangnaihai	1956~1969	y=0.621x-29.8	0.621	P<0.001
	Lanzhou	1950~1969	y=4.02x-315	4.02	P<0.001
	Hekou	1950~1965	y=3.22x-312	3.22	P<0.001
	Longmen	1950~1965	y=10.7x-1240	10.7	P<0.01
	Sanmenxia	1950~1959	y=15.0x-3090	15.0	P=0.078
	Huayuankou	1950~1959	y=15.2x-3818	15.2	P<0.005
	Lijin	1950~1959	y=11.3x-3062	11.3	P<0.005

[a] Here, the independent variable x is annual precipitation ($10^9\times m^3$) during baseline periods, and the dependent variable y is either the corresponding annual water discharge ($10^9\times m^3$) or the sediment load ($10^6\times t$).

Table 3. Decadal variations in precipitation, water discharge and sediment load [a]

Station	Duration	Precipitation (mm/yr)	Water discharge (10^9×m^3/yr)		Sediment load (10^6×t/yr)	
			observation	reconstruction	observation	reconstruction
Tangnaihai	Baseline	478	20.1	19.6	10.5	9.87
	1970s	483 (+ 1 %)	20.4 (+ 2 %)	19.9 (+ 1 %)	12.2 (+ 17 %)	10.3 (+ 4 %)
	1980s	508 (+ 6 %)	24.1 (+ 20 %)	21.5 (+ 10 %)	19.8 (+ 90 %)	12.3 (+ 25 %)
	1990s	476 (- 0.5 %)	17.6 (- 12 %)	19.4 (- 1 %)	10.9 (+ 4 %)	9.67 (- 2 %)
	2000s	467 (- 2 %)	16.5 (- 18 %)	18.9 (- 3 %)	7.1 (- 32 %)	8.98 (- 9 %)
Lanzhou	Baseline	481	336	33.6	114. 7	114.7
	1970s	484 (1 %)	31.8 (- 5 %)	33.9 (+1 %)	62.4 (- 46 %)	117.8 (+ 3 %)
	1980s	497 (3 %)	33.4 (- 1 %)	35.1 (+ 5 %)	40.1 (- 65 %)	128.9 (+12%)
	1990s	471 (- 2 %)	26.0 (- 23 %)	32.7 (- 3 %)	48.7 (- 58 %)	106.2 (- 7 %)
	2000s	472 (- 2 %)	26.4 (- 22 %)	32.7 (- 3 %)	22.7 (- 80 %)	106.8 (- 7 %)
Hekou	Baseline	401	25.0	25.0	162.7	162.7
	1970s	398 (- 1 %)	23.3 (- 7 %)	24.8 (- 1%)	114.9 (- 29 %)	159.3 (- 2 %)
	1980s	395 (- 1 %)	23.9 (- 5 %)	24.5 (- 2 %)	97.8 (- 40 %)	155.7 (- 4 %)
	1990s	390 (- 3 %)	15.7 (- 37 %)	24.0 (- 4 %)	41.1 (- 75 %)	149.3 (- 8 %)
	2000s	379 (- 6 %)	14.0 (- 42 %)	23.0 (- 8 %)	38.9 (- 76 %)	136.0 (- 16 %)
Longmen	Baseline	422	32.0	32.1	1002.4	1002.4
	1970s	406 (- 4 %)	28.5 (- 11 %)	30.5 (- 5 %)	868.0 (- 13 %)	915.5 (- 9 %)
	1980s	401 (- 5 %)	27.6 (- 14 %)	30.0 (- 6 %)	470.0 (- 53 %)	887.3 (- 11 %)
	1990s	393 (- 7 %)	19.8 (- 38 %)	29.3 (- 8 %)	519.2 (- 48 %)	847.1 (- 15 %)
	2000s	391 (- 7 %)	17.0 (- 47 %)	29.2 (- 9 %)	190.3 (- 81 %)	836.5 (- 17 %)
Sanmenxia	Baseline	472	43.4	43.4	1770.6	1770.7
	1970s	441 (- 7 %)	35.8 (- 17 %)	38.6 (- 11 %)	1398.0 (- 21 %)	1449.7 (- 18 %)
	1980s	442 (-6 %)	37.1 (- 15 %)	38.9 (- 10 %)	858.7 (- 52 %)	1468.4 (- 17 %)
	1990s	420 (-11 %)	24.2 (- 44 %)	35.5 (- 18 %)	811.2 (- 54 %)	1239.8 (- 30 %)
	2000s	428 (- 9 %)	19.3 (- 55 %)	36.6 (- 16 %)	361.7 (- 80 %)	1317.2 (- 26 %)
Huayuankou	Baseline	479	44.9	44.9	1423.8	1423.7
	1970s	452 (- 6 %)	38.2 (- 15 %)	40.4 (- 10 %)	1233.1 (- 13 %)	1192.2 (- 16 %)
	1980s	456 (- 5 %)	41.3 (- 8 %)	41.2 (- 8 %)	778.4 (- 45 %)	1230.5 (- 14 %)
	1990s	431 (- 10 %)	25.7 (- 43 %)	35.9 (- 20 %)	682.7 (- 52 %)	955.3 (- 33 %)
	2000s	440 (- 8 %)	23.2 (- 48 %)	37.9 (- 16 %)	110.5 (- 92 %)	1062.8 (- 25 %)
Lijin	Baseline	514	44.5	44.5	1221.0	1221.2
	1970s	458 (- 11%)	31.1 (- 30 %)	33.3 (- 25 %)	898.1 (- 26 %)	815.0 (- 33 %)
	1980s	459 (- 11%)	28.6 (- 36 %)	33.5 (- 25 %)	639.1 (- 48 %)	823.4 (- 33 %)
	1990s	437 (- 15%)	14.1 (- 68 %)	28.5 (- 36 %)	390.2 (- 68 %)	641.9 (- 47 %)
	2000s	447 (- 13%)	14.2 (- 68 %)	30.7 (- 31 %)	143.0 (- 88 %)	723.1 (- 41 %)

[a] Data in parentheses indicate the relative percentage change compared with the corresponding value in the baseline periods, symbol '+'means increase and '-' means decrease)

Table 4. Quantification of the impact

Drainage area	Duration	Water discharge (10^9×m^3/yr) Total change [a]	Water discharge Impact by climate change [b]	Water discharge Impact by human activities [b]	Sediment load (10^6×t/yr) Total change [a]	Sediment load Impact by climate change [b]	Sediment load Impact by human activities [b]
Upper Tangnaiha	1970s	+0.51	-0.01 (-1 %)	+0.52 (+101 %)	+1.93	-0.01 (-0.5 %)	+1.94 (+101 %)
	1980s	+4.22	+1.59 (+38 %)	+2.63 (+62 %)	+9.57	+2.08 (+22 %)	+7.49 (+78 %)
	1990s	-2.28	-0.45 (+20 %)	-1.83 (+80 %)	+0.62	-0.59 (-96 %)	+1.21 (+196 %)
	2000s	-3.43	-0.98 (+29 %)	-2.45 (+71 %)	-3.12	-1.29 (+41 %)	-1.84 (+59 %)
Tangnaihai ~ Lanzhou	1970s	-2.28	+0.36 (-16 %)	-2.64 (+116 %)	-54.16	+3.18 (-6 %)	-57.34 (+106 %)
	1980s	-4.44	-0.02 (+0.4 %)	-4.42 (+100 %)	-84.14	+12.16 (-14 %)	-96.30 (+114 %)
	1990s	-5.31	-0.47 (+9 %)	-4.84 (+91 %)	-66.61	-7.83 (+12 %)	-58.77 (+88 %)
	2000s	-3.79	0.11 (-3 %)	-3.90 (+103 %)	-88.81	-6.64 (+7 %)	-82.17 (+93 %)
Lanzhou ~ Hekou	1970s	+0.04	-0.62 (-1519 %)	+0.66 (+1619 %)	+4.35	-6.57 (-151 %)	+10.92 (+251 %)
	1980s	-0.92	-2.12 (+229 %)	+1.20 (-130 %)	+9.61	-21.32 (-222 %)	+30.92 (322 %)
	1990s	-1.77	-0.11 (+6 %)	-1.66 (+94 %)	-55.64	-5.02 (+9 %)	-50.61 (91 %)
	2000s	-3.40	-1.18 (+35 %)	-2.22 (+65 %)	-31.88	-18.78 (59 %)	-13.09 (41 %)
Hekou ~ Longmen	1970s	-1.86	-1.24 (+67 %)	-0.62 (+33 %)	-86.53	-83.52 (+97 %)	-3.01 (+3 %)
	1980s	-3.29	-1.45 (+44 %)	-1.83 (+56 %)	-467.44	-108.08 (+23 %)	-359.36 (+77 %)
	1990s	-2.86	-1.67 (+58 %)	-1.19 (+42 %)	-361.58	-141.82 (+39 %)	-219.76 (+61 %)
	2000s	-4.46	-0.84 (+19 %)	-3.62 (+81 %)	-688.29	-139.22 (+20 %)	-549.07 (+80 %)
Longmen ~ Sanmenxia	1970s	-4.00	-3.29 (+82 %)	-0.71 (+18 %)	-238.14	-233.91 (+98 %)	-4.24 (+2 %)
	1980s	-1.88	-2.52 (+134 %)	+0.64 (-34 %)	-379.44	-187.03 (+49 %)	-192.42 (+51 %)
	1990s	-6.95	-5.23 (+75 %)	-1.72 (+25 %)	-476.14	-375.50 (+79 %)	-100.64 (+21 %)
	2000s	-8.99	-3.89 (+43 %)	-5.10 (57 %)	-596.72	-287.41 (48 %)	-309.31 (+52 %)
Sanmenxia ~ Huayuankou	1970s	+0.82	+0.32 (+38 %)	+0.50 (+62 %)	+181.84	+89.24 (+49 %)	+92.60 (+51 %)
	1980s	+2.65	+0.78 (+29 %)	+1.88 (+71 %)	+266.44	+108.84 (41 %)	+157.59 (+59 %)
	1990s	-0.06	-1.13 (+1812 %)	+1.07 (-1712 %)	+218.23	+62.21 (+29 %)	+156.02 (+71 %)
	2000s	2.30	-0.21 (-9 %)	+2.50 (+109 %)	+95.46	+92.33 (97 %)	+3.13 (+3 %)
Huayuankou ~ Lijin	1970s	-6.64	-6.77 (+102 %)	+0.13 (-2 %)	-132.18	-174.43 (+132 %)	+42.25 (-32 %)
	1980s	-12.27	-7.27 (+59 %)	-5.00 (+41 %)	+63.52	-204.27 (-322 %)	+267.79 (+422 %)
	1990s	-11.20	-6.99 (+62 %)	-4.21 (+38 %)	-89.68	-110.51 (+123 %)	+20.83 (-23 %)
	2000s	-8.55	-6.82 (+80 %)	-1.74 (+20 %)	235.40	-136.91 (-58 %)	+372.30 (+158 %)
Upper reaches	1970s	-1.73	-0.26 (+15 %)	-1.47 (+85 %)	-47.87	-3.40 (+7 %)	-44.47 (+93 %)
	1980s	-1.14	-0.55 (+48 %)	-0.59 (+52 %)	-64.97	-7.08 (+11 %)	-57.89 (+89 %)
	1990s	-9.37	-1.03 (+11 %)	-8.34 (+89 %)	-121.63	-13.45 (+11 %)	-108.18 (+89 %)
	2000s	-10.62	-2.05 (+19 %)	-8.58 (+81 %)	-123.80	-26.71 (+22 %)	-97.10 (+78 %)
Middle reaches	1970s	-5.04	-4.22 (+84 %)	-0.82 (+16 %)	-142.84	-228.19 (+160 %)	+85.35 (-60 %)
	1980s	-2.52	-3.20 (+127 %)	0.68 (-27 %)	-580.45	-186.27 (+32 %)	-394.18 (+68 %)
	1990s	-9.87	-8.03 (+81 %)	-1.84 (+19 %)	-619.49	-455.11 (+73 %)	-164.38 (+27 %)
	2000s	-11.16	-4.94 (+44 %)	-6.22 (+56 %)	-1189.56	-334.31 (+28 %)	-855.25 (+72 %)
Lower reaches	1970s	-6.64	-6.77 (+102 %)	+0.13 (-2 %)	-132.18	-174.43 (+132 %)	+42.25 (-32 %)
	1980s	-12.27	-7.27 (+59 %)	-5.00 (+41 %)	+63.52	-204.27 (-322 %)	+267.79 (+422 %)

	1990s	-11.20	-6.99 (+62 %)	-4.21 (+38 %)	-89.68	-110.51 (+123 %)	+20.83 (-23 %)
	2000s	-8.55	-6.82 (+80 %)	-1.74 (+20 %)	+235.40	-136.91 (-58 %)	+372.30 (+158 %)
Whole basin	1970s	-13.41	-11.25 (+84 %)	-2.16 (+16 %)	-322.90	-406.03 (+126 %)	+83.13 (-26 %)
	1980s	-15.93	-11.02 (+69 %)	-4.91 (+31 %)	-581.90	-397.61 (+68 %)	-184.29 (+32 %)
	1990s	-30.44	-16.05 (+53 %)	-14.39 (+47 %)	-830.80	-579.07 (+70 %)	-251.73 (+30 %)
	2000s	-30.33	-13.80 (+46 %)	-16.53 (+55 %)	-1077.97	-497.92 (+46 %)	-580.04 (+54 %)

[a] Total change is the value compared with the value in baseline periods; [b] Data in parentheses indicate the percentage change divided by the total change, and the symbol '-' means negative effect on total change, symbol '+' means positive effect on total change.

Table 5. Hyper-irrigation areas in the Yellow River basin [a]

Location	Area (km^2)	Hyper-irrigation area (km^2)
Tangnaihai~Lanzhou	100,579	0.07
Lanzhou~Hekou	145,347	1.16
Hekou~Longmen	129,654	0.15
Longmen~Sanmenxia	190,869	2.09
Sanmenxia~Huayuankou	41,615	0.07
Downstream of the Huayuankou	21,833	3.58

[a] Data summarized in the 1990s; Source: Yang et al. (2004)

Table 6. Tributary reservoirs in the Yellow River basin

Location	Amount	Storage capacity ($10^6 \times m^3$)	Accumulated siltation capacity ($10^6 \times m^3$)		
			1969	1979	1989
Upstream of Lanzhou	16	91	0.4	1.24	3.02
Lanzhou~Hekou	60	1300	143	393	655
Hekou~Longmen	134	2176	79	341	716
Longmen~Sanmenxia	297	4417	421	931	1364
Sanmenxia~Huayuankou	75	2990	44	112	165

Source: Yang et al. (2004)

Table 7. Area of soil conservation practices in Hekou~Longmen sub-catchment

Time	Area of soil conservation practices (km^2)				
	Level terrace	Afforestation	Grass-planting	Check dam	Total
1959	331	1,513	357	28	2,229
1969	1,158	3,423	383	154	5,118
1979	2,305	8,818	1,045	395	12,563
1989	3,448	19,862	2,114	563	25,987
1996	4,859	25,373	2,408	682	33,322

Source: Ran et al. (2000)

Table 8. Effects of different soil conservation practices in the Middle reaches of Yellow River basin

Soil conservation practices	Ration for maintaining runoff (m^3/km^2)	Ration for maintaining sediment (t/km^2)
Level terrace	3.8	0.8
Check dam	6.1	370
Paddy field	3.8	0.8
Afforestation	2.5	0.3
Garden	2.5	0.3
Grass-planting	1.3	0.2

Source: Jiao et al. (2004)

Figure Captions

Figure 1. Yellow River Basin: Location of hydrological and meteorological stations, and major reservoirs; Each figure in parentheses indicates the year reservoir operation commenced.

Figure 2. Estimates of quantitative hydrological response to climate change and human activities at Hekou station. Intervals ① and ② respectively indicate the impacts of climate change and human activities.

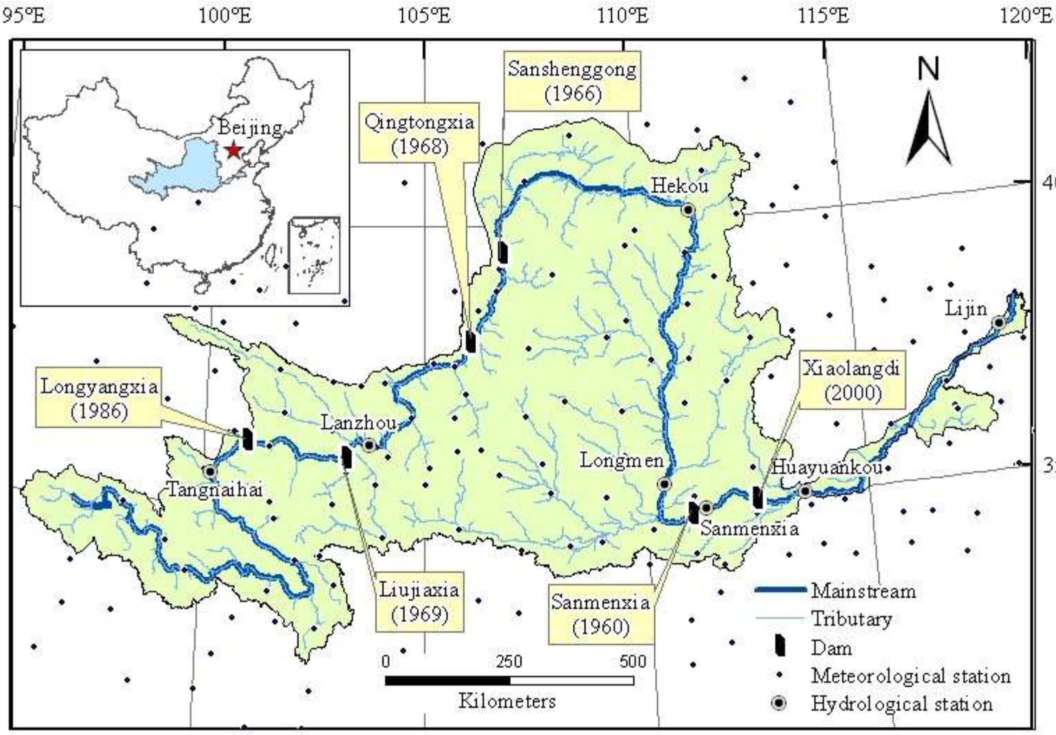
Figure 3. Regression analyses between annual regional precipitation and annual water discharge, and annual regional precipitation and sediment load during the baseline periods. Here the annual water discharge and annual sediment load are taken directly from observations at the respective gauging stations, whereas the annual precipitation is interpolated from meteorological data in the drainage area upstream of the corresponding hydrological stations.

Figure 4 Accumulative area affected by soil conservation practices in the Yellow River Basin from 1997 to 2008

Figure 5. Change of bed elevation at Tongguan from 1950 to 2008

Figure 6. Average annual groundwater baseflow during 1960~2000 in the Yellow River

Figure 1



95°E
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Xiaolangdi
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Longyangxia
(1986)
Lanzhou
Longmen
Huayuankou
Tangnaihai
Sanmenxia
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250
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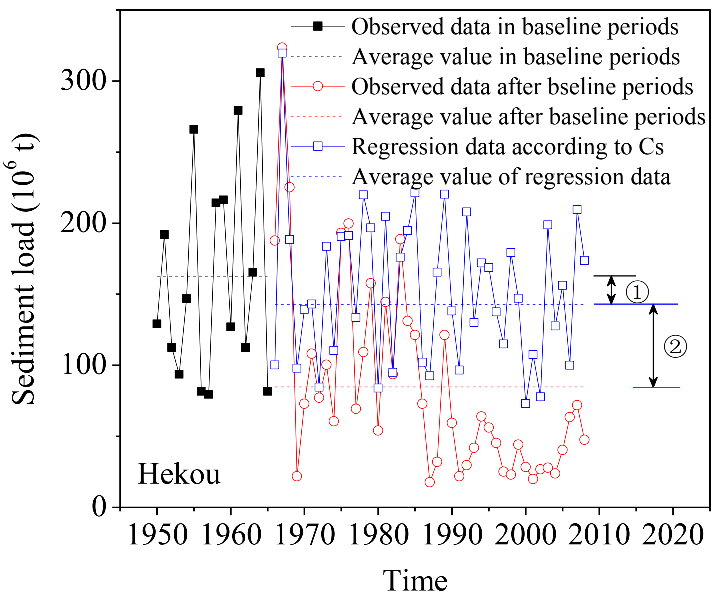
Figure 2


Observed data in baseline periods
Average value in baseline periods
Observed data after bseline periods
Average value after baseline periods
Regression data according to Cs
Average value of regression data
Hekou
①
②
Sediment load (10^6 t)
Time
0
100
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300
1950
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2000
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2020

Figure 3

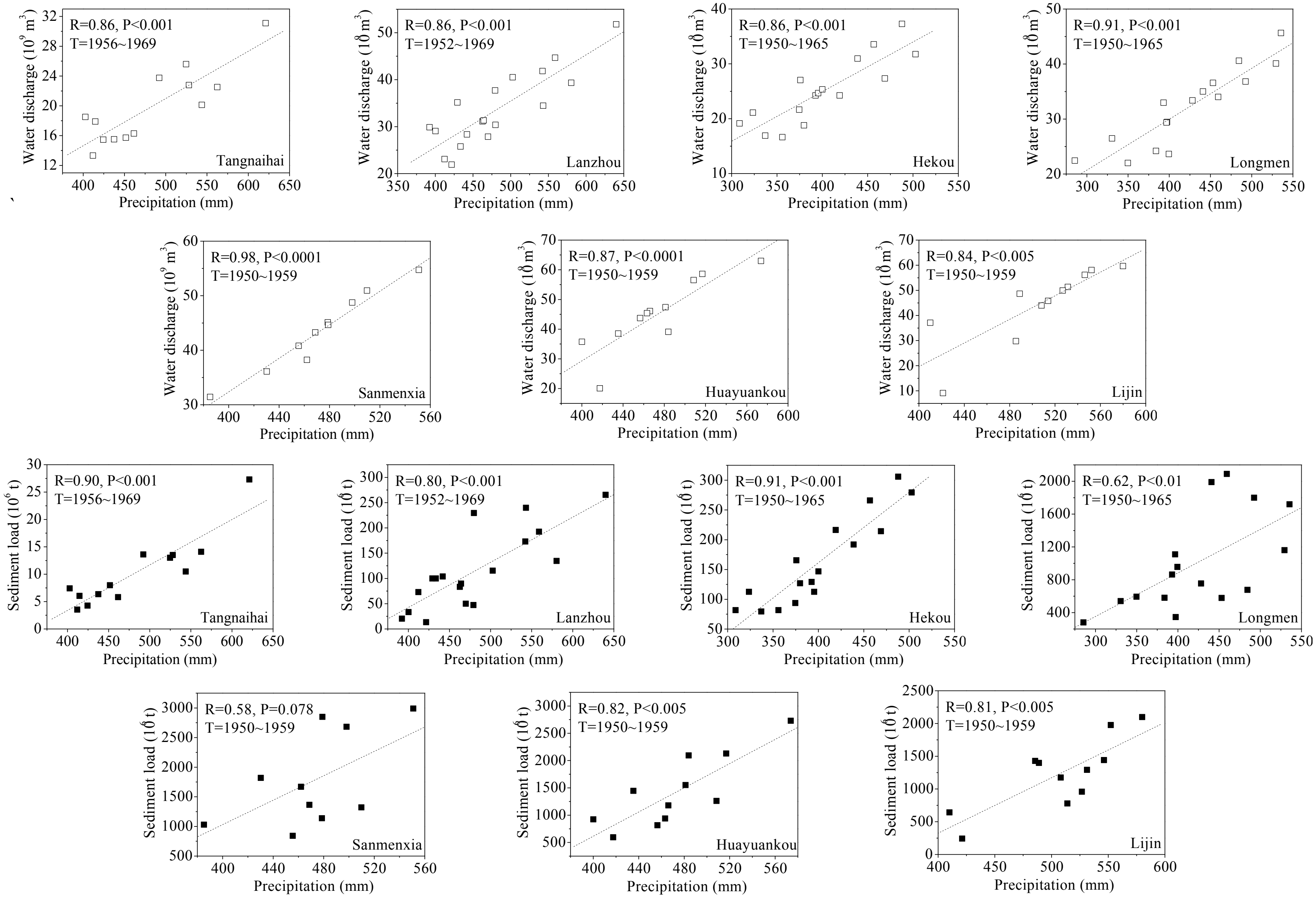
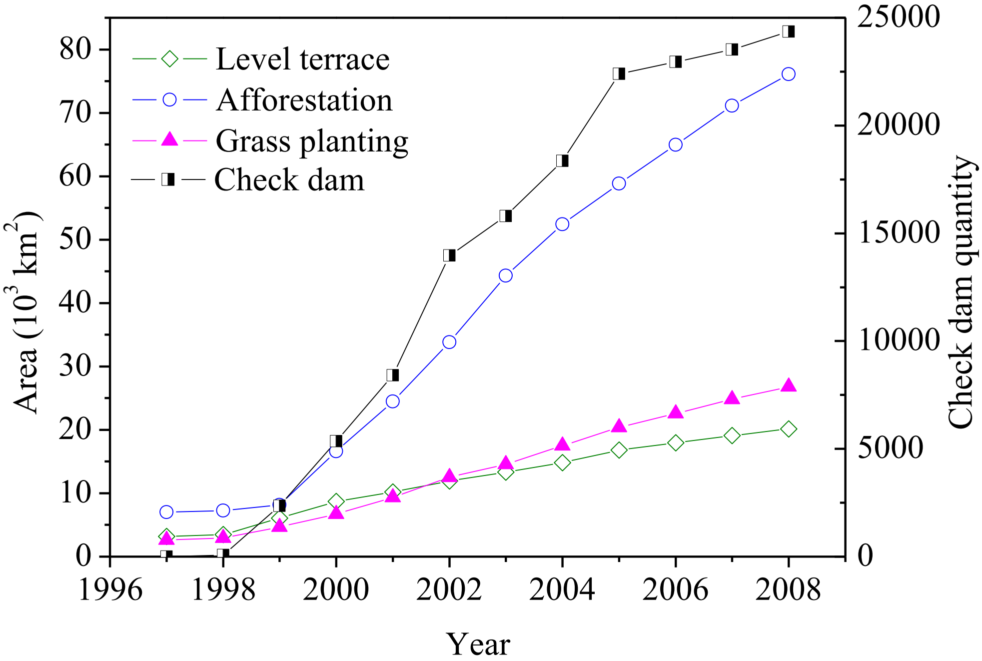
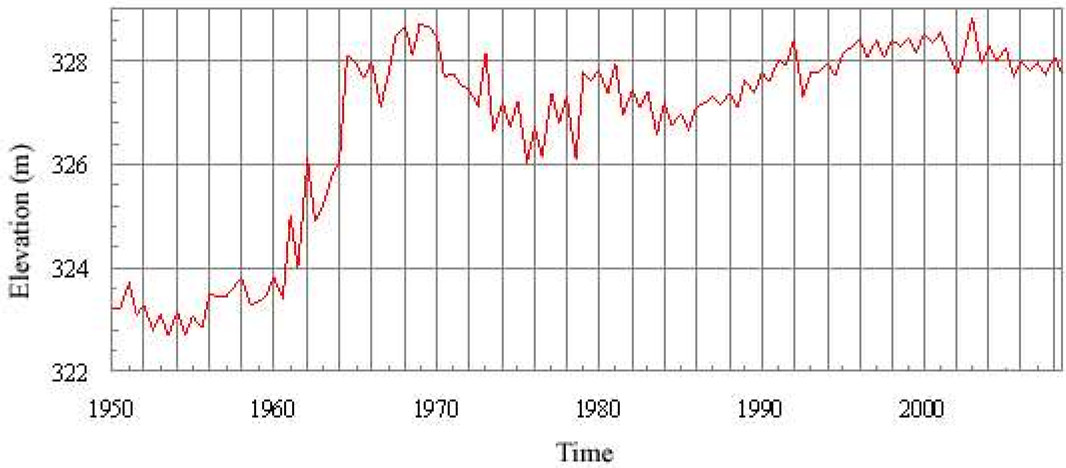

R=0.86, P<0.001
T=1956~1969
Tangnaihai
Water discharge (10^9 m^3)
Precipitation (mm)
R=0.86, P<0.001
T=1952~1969
Lanzhou
Water discharge (10^8 m^3)
Precipitation (mm)
R=0.86, P<0.001
T=1950~1965
Hekou
Water discharge (10^8 m^3)
Precipitation (mm)
R=0.91, P<0.001
T=1950~1965
Longmen
Water discharge (10^8 m^3)
Precipitation (mm)
R=0.98, P<0.0001
T=1950~1959
Sanmenxia
Water discharge (10^9 m^3)
Precipitation (mm)
R=0.87, P<0.0001
T=1950~1959
Huayuankou
Water discharge (10^8 m^3)
Precipitation (mm)
R=0.84, P<0.005
T=1950~1959
Lijin
Water discharge (10^8 m^3)
Precipitation (mm)
R=0.90, P<0.001
T=1956~1969
Tangnaihai
Sediment load (10^6 t)
Precipitation (mm)
R=0.80, P<0.001
T=1952~1969
Lanzhou
Sediment load (10^6 t)
Precipitation (mm)
R=0.91, P<0.001
T=1950~1965
Hekou
Sediment load (10^6 t)
Precipitation (mm)
R=0.62, P<0.01
T=1950~1965
Longmen
Sediment load (10^6 t)
Precipitation (mm)
R=0.58, P=0.078
T=1950~1959
Sanmenxia
Sediment load (10^6 t)
Precipitation (mm)
R=0.82, P<0.005
T=1950~1959
Huayuankou
Sediment load (10^6 t)
Precipitation (mm)
R=0.81, P<0.005
T=1950~1959
Lijin
Sediment load (10^6 t)
Precipitation (mm)

Figure 4



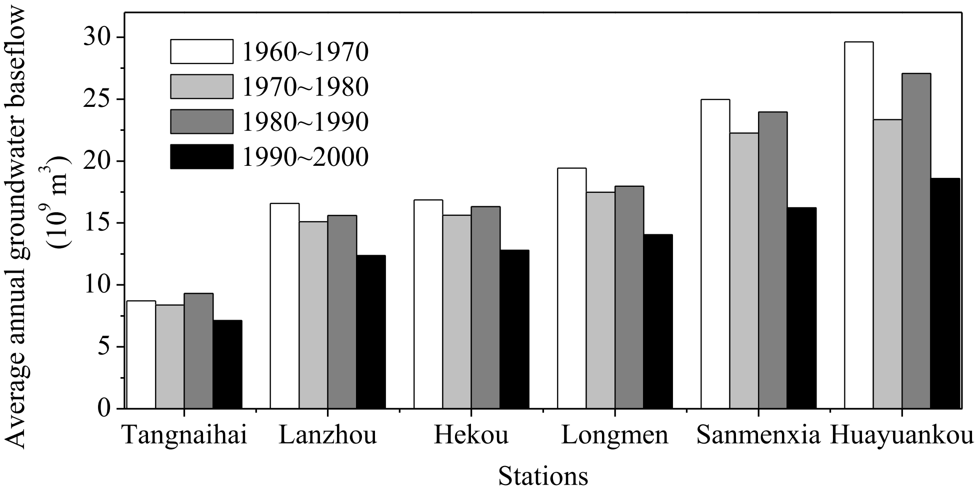
Level terrace
Afforestation
Grass planting
Check dam
Area (10^3 km^2)
Check dam quantity
Year
0
10
20
30
40
50
60
70
80
0
5000
10000
15000
20000
25000
1996
1998
2000
2002
2004
2006
2008

Figure 5



Elevation (m)
328
326
324
322
1950
1960
1970
1980
1990
2000
Time

Figure 6


Average annual groundwater baseflow
(10^9 m^3)
1960~1970
1970~1980
1980~1990
1990~2000
0
5
10
15
20
25
30
Tangnaihai
Lanzhou
Hekou
Longmen
Sanmenxia
Huayuankou
Stations